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Voltage regulation studies of brushless synchronous generator.

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VOLTAGE REGULATION STUDIES OF BRUSHLESS SYNCHRONOUS GENERATOR

by

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ABSTRACT

In the present dissertation an effort has been made to develop a mathematical simulation of the brushless synchronous generator for voltage regulating system studies. This representation, which is particularly suited to a digital-analog simulator program, includes variable-speed operation, various values of transmission line parameters when connected as a load and different levels of infinite bus-bar voltage.

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NOMENCLATURE

Main Symbols

e	voltage (Instantaneous value)
i	current (Instantaneous value)
L	total self inductance
l	leakage inductance
t	time in seconds
f	torque
τ	time constant
p	operator d/dt
H	machine inertia constant in KW sec/KVA
ω_o	angular velocity of infinite bus in radians per second (synchronous speed)
ν	angular velocity of rotor in radians per second
θ	angular position of rotor in space
δ	load angle of synchronous machine with respect to bus
ψ	flux linkage
E	fixed supply voltage
J	moment of inertia
k_v	gain of the amplifier
r	resistance
X	reactance

Subscripts

a	phase A, armature
d	direct axis quantity
q	quadrature axis quantity
f	field winding
k	damper winding
m	magnetizing, maximum
md	direct axis mutual
r	reference
e	electrical, external
t	mechanical
ae	phase A of a.c. exciter
o	open circuit
rf	reference
er	error

I

INTRODUCTION

1.1 Review

A new type of excitation system has been developed for use in utility industry in which the collector, the collector brushes the commutator and the commutator brushes can be eliminated. Present development in brushless excitation can be traced back to about ten years, when this system was used in aircraft voltage regulators. This system consists of an a.c. exciter with a set of rotating rectifiers mounted on the main generator shaft. Usually these rectifiers are mounted on the cooling fan of the generator which provides an excellent heat sink for the rectifier. The rectifiers are supplied with a.c. power from the a.c. exciter through the hollow shaft of the generator. The transmission of power to generator field is thus achieved without having any brush gear.

Selenium rectifiers were first tried at 3600 R.P.M. to furnish the a.c. excitation requirements for large generators but their inability to do so delayed the application in the electric utility industry. However silicon diode rectifiers have since been tested and found to be ideal for this application.[1]

Various types of exciters have been used to meet the requirements of exciting the field of large turbo-generators. D.C. rotating type electronic excitation, and in some cases external dry type rectifiers have been used. In all these cases power must be transferred from the

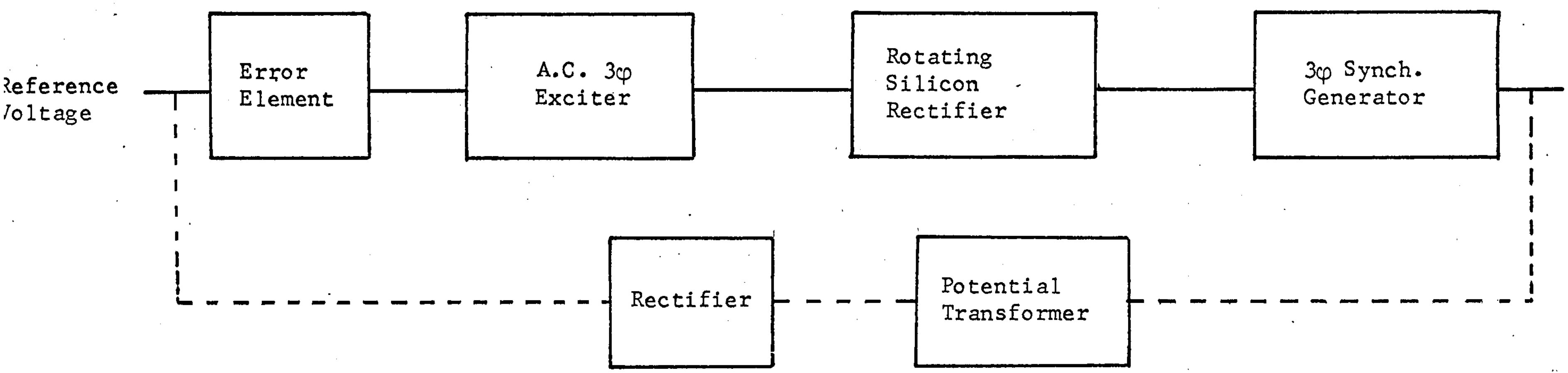
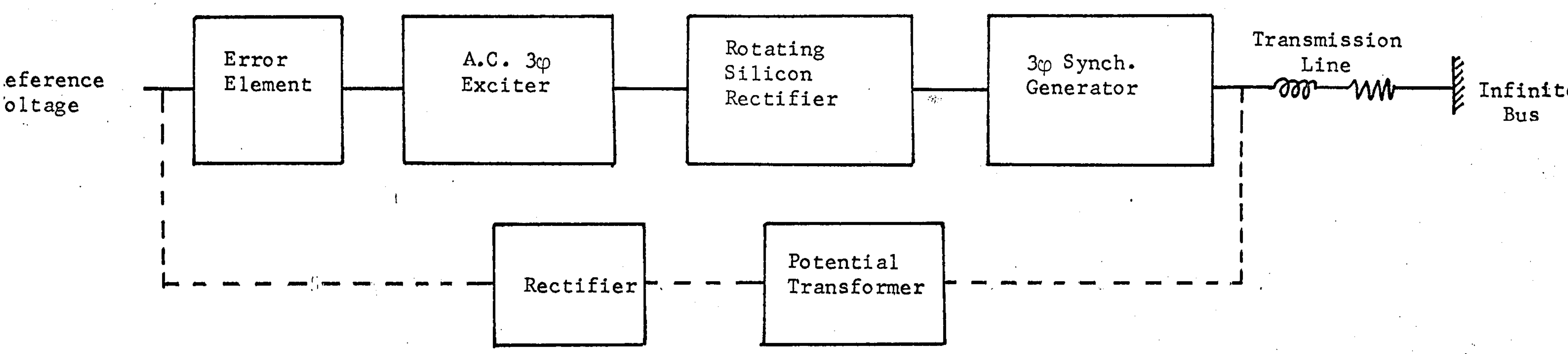


Fig. 1
Schematic Block Diagram of the Voltage Regulating System



Schematic Block Diagram of the Voltage Regulating System as Connected to an Infinite Bus-Bar through a Transmission line Fig. 2

device to the field of a.c. generator which requires collector rings and brushes. The design of large capacity collector rings becomes more difficult as the power to be transferred becomes larger.

Consequently, improvement in reliability of this new excitation system provides various advantages. The system is free from carbon dust and maintenance of insulated parts is materially improved.

1.2 System

The fundamental components of the brushless excitation system are shown in block diagram form in Fig. 1. The solid line connects the major system components and dashed line indicates feed back path to improve the stability and performance of the regulating system. The primary purpose of the regulating system is to maintain a static regulation of generator terminal voltage within 0.5% of preset value. Moreover the system should recover rapidly and with high degree of stability to external transient disturbances like sudden changes in load, short circuit and so on. The generator terminal voltage is continuously monitored by a potential transformer and rectified to give a d.c. signal. It is compared with reference voltage source in error element. The error signal is amplified and applied to the field of a.c. 3φ exciter. The exciter terminal voltage is rectified by 3 phase rotating silicon rectifier full-wave bridge, the output of which excites the synchronous generator field. This completes the voltage-regulating loop, (Fig. 1).

1.3 Scope of Studies

In the present dissertation an attempt has been made to develop a general block diagram representation of the brushless excitation system when applied to voltage regulating system studies. A simple voltage regulator arrangement is being considered (Fig. 2). The system studied consists of a single synchronous machine connected to an infinite bus through a transmission line. The representation which is suited particularly to analogue type computation, includes variable speed operation, various values of transmission line parameters and levels of infinite bus voltage. The effect of saliency and damper circuits is also considered.

1.4 Pactolus

Because of inadequate facilities in analogue computation, a digital-analog simulator program, commonly known as 'Pactolus' has been used on 1620 IBM digital computer to carry out various studies. This program is written in Fortran II, simulates almost all the elements of electronic analogue computer. Though this program maintains single precision, it lacks in some respects the analogue computer. The integration is done by well known Rungg-Kutta method. Since the digital computer works on discrete point basis the process of solving various differential equations of the synchronous machine having different non-linearities involves time consuming job. However the method appeared to be quite flexible.

II

FUNDAMENTAL MACHINE EQUATIONS

2.1 General

The first step of todays development of generalized theory was taken by Blondel. His 'two-reaction theory' of the steady state operation of the salient-pole synchronous machine is recognized today as one of unquestioned competence. A classical application of the concept is found in the so-called Park's equations, which describe the dynamic characteristics of synchronous machine. The fundamental set of equations is derived for an idealized two-pole machine, which is approximately equivalent to the actual machine, in accordance with certain well-defined assumptions.

2.2 Assumptions

The general theory of electric machines, as defined by Park [2] is based on certain assumptions, in order to idealize them for studies. The principal assumptions are that there is no saturation and that space harmonics in the flux wave may be neglected. In addition the following generally accepted assumptions have been considered.

i) Symmetrical conditions exist on the system, i.e. zero sequence quantities are zero.

ii) Per-unit mutual inductances for all the coils on any one axis are equal.

iii) Damping circuit is represented by a single coil on each axis.

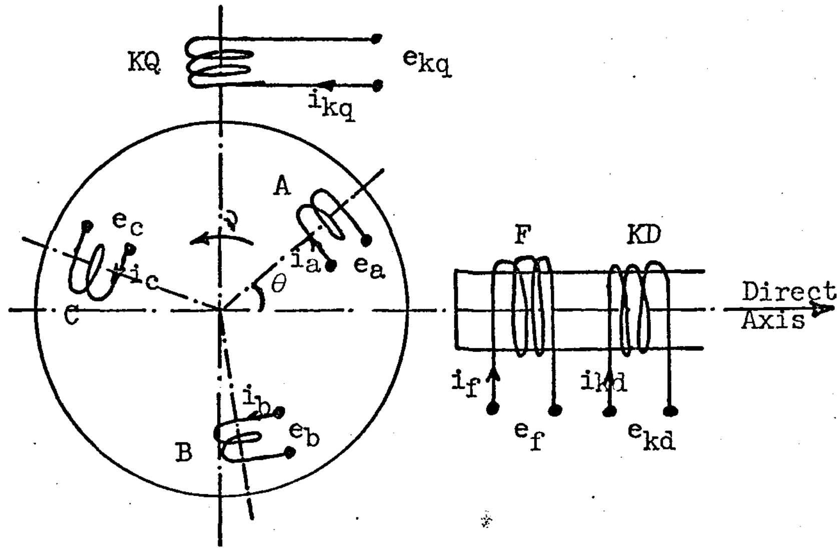


Fig: 3 Diagram of an Idealised Synchronous Machine.

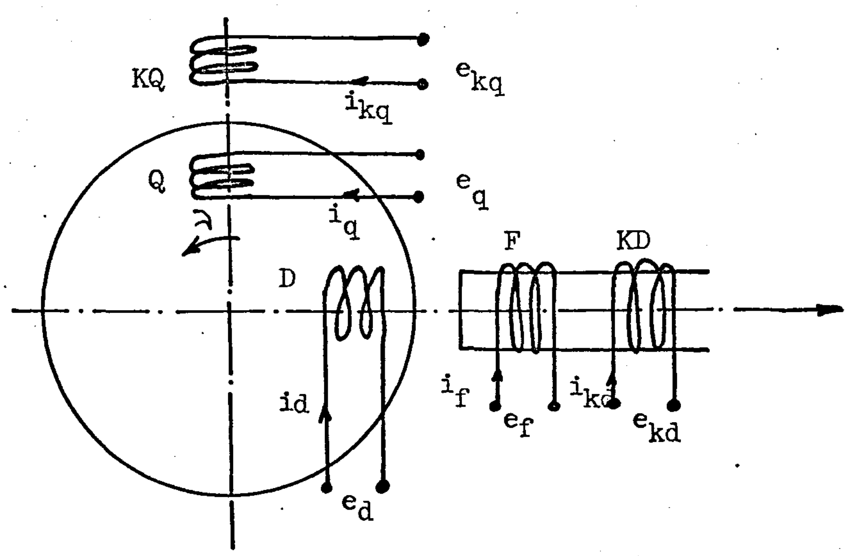


Fig: 4 Diagram of a Synchronous Machine with two damper coils.

2.3 Per-Unit System

Very often, computations relating to machines, transformers, and systems of machines are carried out in the per-unit form, i.e. with all pertinent quantities expressed as decimal fractions of appropriately chosen base values. At present there are various per-unit systems in use. All the equations and other quantities in this thesis are expressed in per-unit basis as defined by Rankin[3].

Rankin terms the 'x_{ad}' as base in the base-current ratio. In the present work that has been taken as standard base.

2.4 Sign Convention

Throughout the working of this thesis, sign convention followed by Adkins[4] is being used. As shown in Fig. 3, axis of the coil representing the armature phase A makes angle θ in counter-clockwise direction with direct axis. Only one of the two salient poles is indicated. The stator carries a field coil F and damper coils KD and KQ. The axis of the pole on which the field coil F is wound is called the direct-axis of the machine, while the axis 90^o away in counter-clockwise direction is called quadrature axis of the machine.

The coil voltages are assumed positive when impressed on the coils from an external source and the currents are measured in the same direction as driving positive voltage.

Positive current is assumed to produce positive flux in the direction along the axis away from centre. Positive electric torque is obtained when mechanical power is entering into machine from outside at a positive speed. Thus generator action has positive mechanical torque.

2.5 Fundamental Equations

(a) Voltage equations

With the assumptions and the sign convention considered in the previous sections fundamental voltage equations of the synchronous machine can be written in terms of corresponding currents and flux linkages. By Park's transformation[4] the three phase voltages and three phase currents Viz. e_a, e_b, e_c and i_a, i_b, i_c are transformed to new fictitious quantities $e_d, e_q, e_o, i_d, i_q, i_o$ which differ from but are related to the actual quantities. The following equations are obtained, neglecting zero sequence quantities in view of assumption (i) Section 2.2.

$$e_d = p\psi_d + v\psi_q + r_a \cdot i_d \tag{1}$$

$$e_q = -v\psi_d + p\psi_q + r_a \cdot i_q \tag{2}$$

(b) Equations of the machine connected to a constant source voltage

When a synchronous generator is connected to a system having constant supply voltage the load angle δ comes into picture. The method introduces angle δ by which the rotor position lags behind the position it would have during synchronous operation at no-load. In order to understand the physical meaning of the angle δ it is necessary to visualize in Fig. 3 an imaginary reference axis rotating at synchronous speed ω_o and occupying the position that phase A would have if machine ran steadily with the armature winding connected to a constant supply source but with no current in it. Under steady conditions δ is constant. The value of angle δ is positive for motoring and negative for generating action, and zero for no-load condition.

The position θ_r of the reference axis at any instant is given by

$$\theta_r = \omega_o t \tag{3}$$

and with a varying speed the machine position is

$$\theta = \omega_o t - \delta \tag{4}$$

The phase voltage e_a can be expressed as

$$\begin{aligned} e_a &= E_m \sin\omega_o t \\ &= E_m \sin(\theta+\delta) \\ &= E_m \sin\delta\cdot\cos\theta + E_m \cos\delta\cdot\sin\theta \end{aligned} \tag{5}$$

where E_m is the maximum value of fixed supply voltage. By Park's transformation e_a can be related to e_d and e_q as

$$e_a = e_d \cos\theta + e_q \sin\theta \tag{6}$$

The value of e_a in Eqn.(5) and (6) must be same at every t, hence comparing the coefficients of Eqn. (5) and (6) gives

$$e_d = E_m \sin\delta \tag{7}$$

$$e_q = E_m \cos\delta \tag{8}$$

The speed is obtained by differentiating Eqn. (4)

$$\nu = \omega_o - p\delta \tag{9}$$

Substituting the values of the above equations in Eqn. (1) and (2) the modified general equations are obtained

$$e_d = E_m \sin\delta = p\psi_d + \omega_o\psi_q + r_a i_d - \psi_q\cdot p\delta \tag{10}$$

$$e_q = E_m \cos\delta = -\omega_o\psi_d + p\psi_q + r_a i_q + \psi_d\cdot p\delta \tag{11}$$

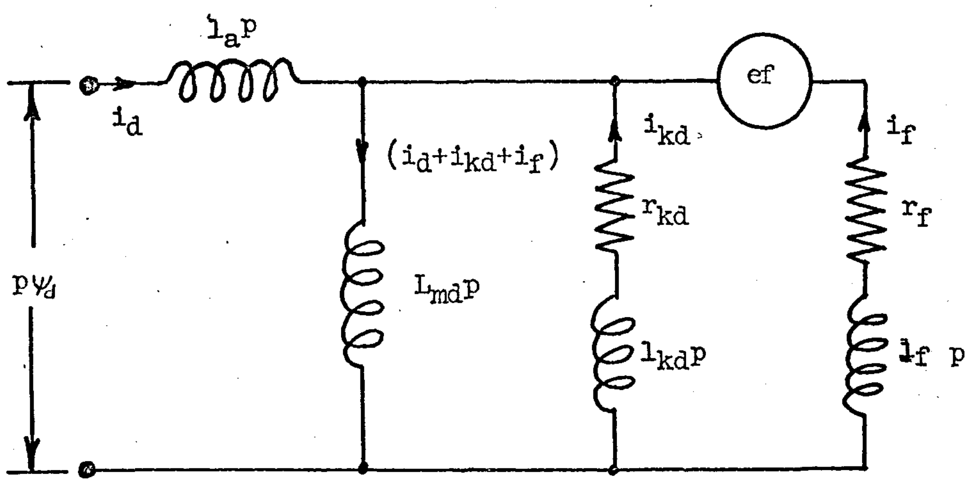


Fig: 5 Direct axis

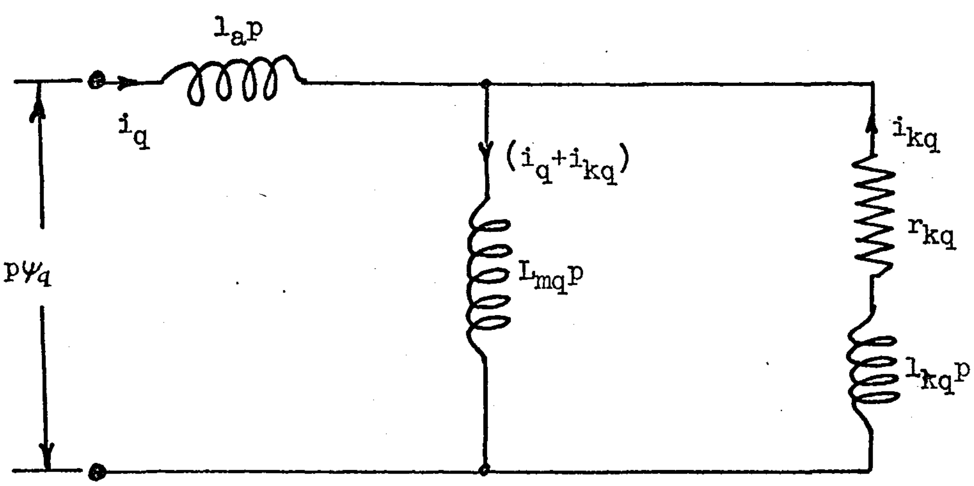


Fig : 6 Quadrature axis

Equivalent circuits of a synchronous Machine

2.6 Simplified Equations of a Synchronous Machine with Two Damper Coils

For the synchronous machine problem under consideration the equations used are those of simplified machine Fig. 4 with one damper coil KD on the direct axis and one damper coil KQ on the quadrature axis. With the assumptions already made in Section 2.2 the problem becomes easier to handle. It is assumed that three per-unit mutual inductances on direct axis are all equal.

The equations are

(i) Direct axis equations:

$$\psi_d = L_{md} \cdot i_f + L_{md} \cdot i_{kd} + (L_{md} + l_a) i_d \tag{12}$$

$$e_f = [r_f + (L_{md} + l_f)p]\, i_f + L_{md}\, p\, i_{kd} + L_{md}\, p\, i_d \tag{13}$$

$$e_{kd} = L_{md}\, p\, i_f + [r_{kd} + (L_{md} + l_{kd})\, p] i_{kd} + L_{md}\, p\, i_d \tag{14}$$

(ii) Quadrature axis equations:

$$\psi_q = L_{mq} \cdot i_{kq} + (L_{mq} + l_a)\, i_q \tag{15}$$

$$e_{kq} = [r_{kq} + (L_{mq} + l_{kq})\, p]\, i_{kq} + L_{mq}\, p\, i_q \tag{16}$$

In practice the impressed voltages e_{kd} and e_{kq}, that of damper windings KD and KQ are almost always zero.

2.7 Equivalent Circuits

The equivalent circuits are of particular interest from the point of view of devising suitable simulating equipment. Figs. 5 and 6 show two equivalent circuits, one for each axis which can be used to assist in the analysis of the synchronous machine. By solving the network in Fig.5,6 it is evident that they satisfy the equations (12) through

(16). Further development is made in the next chapter, for analogue representation.

2.8 The General Torque Equation

At any instant the torque developed by the machine depends on the current flowing in the windings. The torque developed by the interaction between the flux and current is called electrical torque. The rotational voltage terms $-\nu\psi_d$ and $\nu\psi_q$ contribute towards the electrical power. The electrical power is

$$Pe = \frac{1}{2}\left[(\text{rotational component of } e_d) \times i_d\right] + \left[(\text{rotational component of } e_q) \times i_q\right]$$

substituting for these components from Eqn. (1),(2)

$$Pe = \frac{\nu}{2}\left(\psi_q\, i_d - \psi_d\, i_q\right) \tag{17}$$

Hence per-unit electrical torque f_e is given by [2]

$$f_e = -Pe\,\frac{\omega_o}{\nu} = \frac{\omega_o}{2}\left(\psi_d\, i_q - \psi_q \cdot i_d\right) \tag{18}$$

If f_t is the instantaneous applied torque, and $J\,\frac{d\nu}{dt}$ is the accelerating torque[2], then

applied torque = electrical torque + accelerating torque

$$f_t = f_e + J\,\frac{d\nu}{dt} \tag{19}$$

Differentiating Eq. (4) two time the acceleration is obtained, thus

$$\frac{d^2\theta}{dt^2} = -p^2\delta$$

but

$$\frac{d^2\theta}{dt^2} = \frac{d\nu}{dt}$$

hence

$$\frac{dv}{dt} = -p^2\delta \tag{20}$$

The unit torque in per-unit systems, is defined as[4] the torque which produces unit power at the nominal speed ω_o. The moment of inertia of the machine, in per-unit system is expressed by inertia constant H, and defined[4] by the following relation:

$$H = \frac{\text{Stored energy at synchronous speed in K.W. sec.}}{\text{Rated KVA}}$$

The inertia constant and the moment of inertia has following relation:

$$H = \frac{1}{2} J\omega_o \tag{21}$$

Hence the torque equation (19) can be stated as:

$$f_t = \frac{\omega_o}{2} (\psi_d i_q - \psi_q i_d) - \frac{2H}{\omega_o} p^2\delta \tag{22}$$

III

RECTIFIER

3.1 General

Modern large machines require more excitation power than can be conveniently handled by conventional d.c. exciters. Rectifiers provide a solution to this problem, and give a field supply having greater inherent reliability, faster response if needed and a useful saving of space. Various types of rectifier cells are available but most commonly used for field excitation of rotating machines are p-n type silicon rectifier. As shown in Fig. 7 the actual p-n junction assembly is usually attached to copper base on the one side and to a flexible connection on the other, using special hard solder without flux, with the interposition of a disc of tungsten or molybdenum on one or both sides. Without these later features the large expansion mismatch between the silicon and the copper would soon lead to a fatigue failure in case of frequently fluctuating load.[5]

3.2 Rectifier Circuit Theory

Rectifier-circuit theory consists essentially in a study of periodically recurring transients. In order to reduce the problem to its simplest form, it is convenient to make the following basic assumptions.[6]

(i) The Rectifier output is considered to be a pure direct current, so that the anode currents are then of rectangular

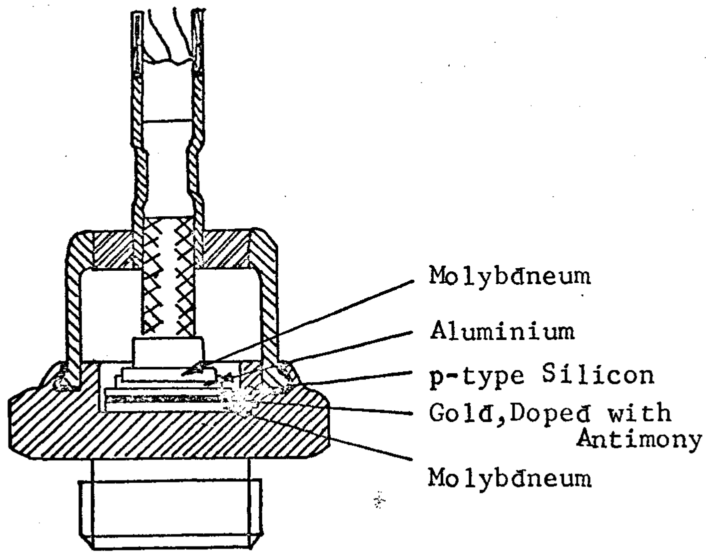


Fig. 7

Section of a Typical
Silicon Rectifier Cell

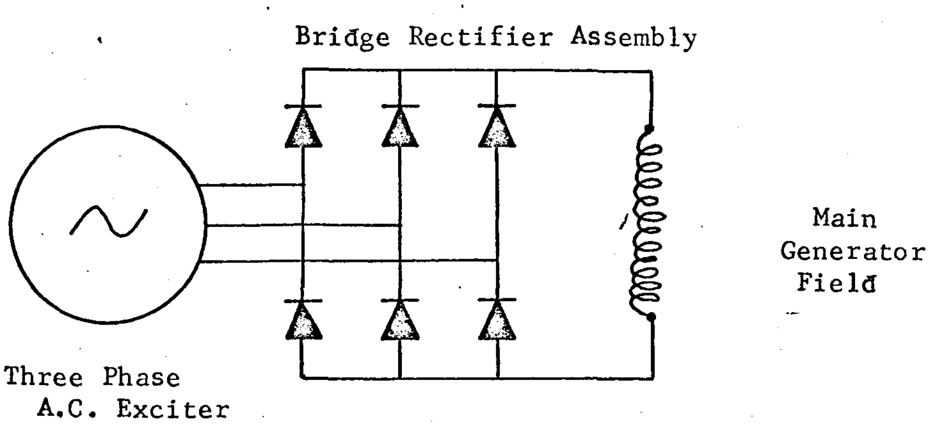


Fig. 8

Three phase Bridge Rectifier with
Generator Field as a Load

wave-form. (Fig. 10)

(ii) The alternating supply voltage is assumed to be sinusoidal under all conditions of rectifier loading.

(iii) Forward voltage drop and inverse current effects are neglected.

(iv) Effect of a.c. exciter reactance is neglected.

The essential principles of three-phase full wave rectification are well illustrated by three-phase circuit as shown in Fig. 8. If the inductance is assumed to be so large that load current is constant, the current and voltage relations are as in Figs. 9 and 10. An anode begins to conduct as soon as its voltage becomes more positive than that of the preceding anode. In this case, each anode conducts for one-sixth the time. It is evident from the voltage wave that with this bridge rectifier arrangement the output voltage wave form is fairly smooth. Hence smaller inductance would be required to maintain the same smoothness of current than for half wave rectifier. The ripple of the output voltage is absorbed by the inductance.

The input to the bridge rectifier is from the a.c. exciter and its wave form is shown in Fig. 9. The output voltage of a rectifier bridge of six anodes may be determined by referring to Fig. 11. In this figure e_f is the average value of the d.c. output voltage and e_{ae} is the r.m.s. value of the a.c. exciter phase A voltage. The average value of the output voltage is,[6]

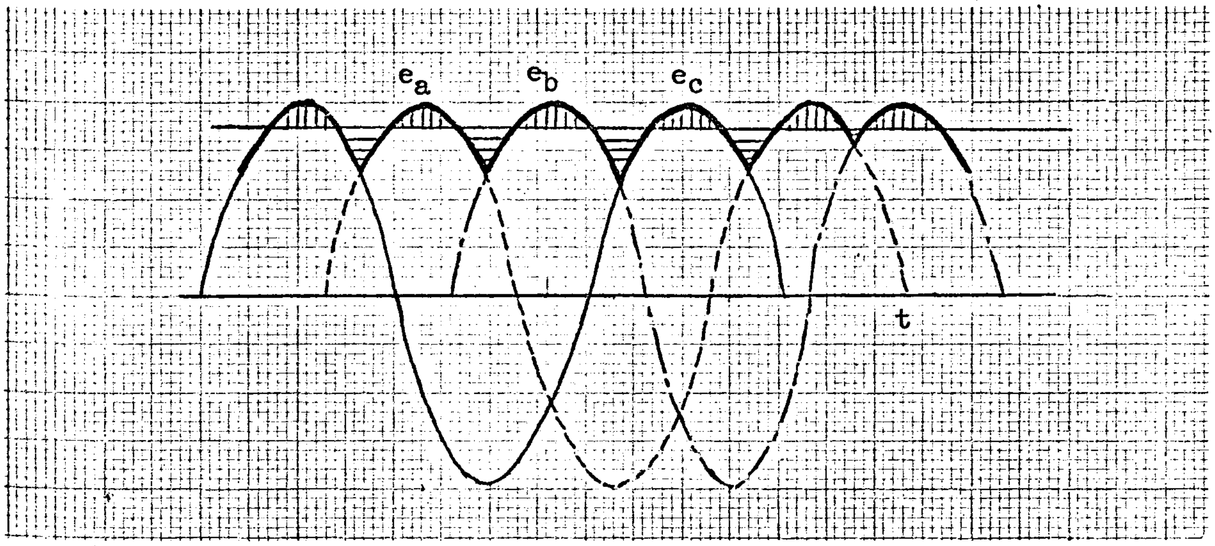


Fig. 9

Three Phase Voltage Wave(Input to the Bridge Rectifier)

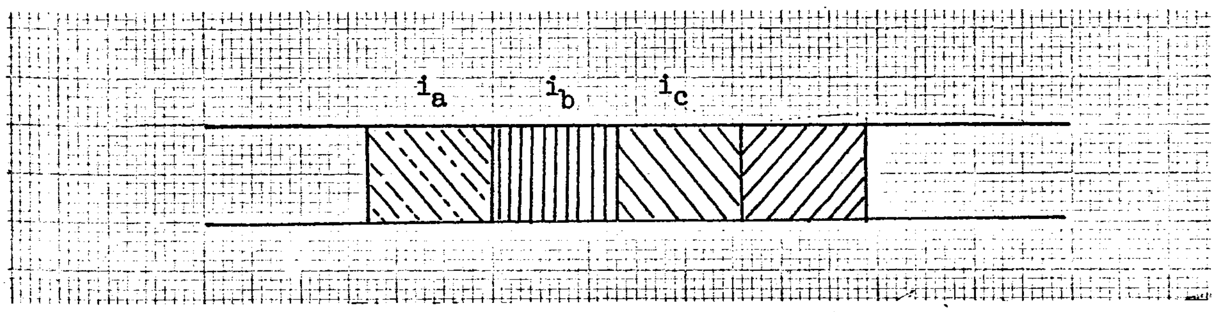


Fig. 10

Output Current Relation of the Bridge Rectifier

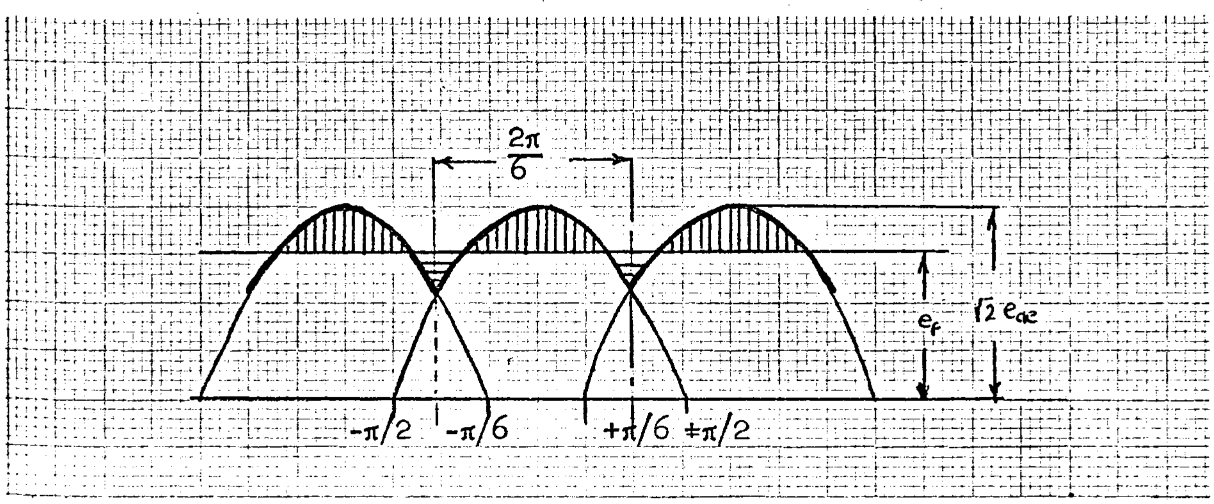


Fig. 11

Harmonic Contents of the Voltage Wave

$$e_f = \frac{6}{2\pi} \int_{-\frac{\pi}{6}}^{+\frac{\pi}{6}} \sqrt{2}\, e_{ae} \cos\omega t \cdot d\omega t$$

$$= \frac{6\sqrt{2}}{2\pi}\, e_{ae} \left[\sin \omega t\right]_{-\frac{\pi}{6}}^{+\frac{\pi}{6}}$$

$$= \frac{6\sqrt{2}}{2\pi} \cdot 2 \cdot e_{ae} \cdot \sin \frac{\pi}{6}$$

$$= \frac{6\sqrt{2}}{\pi}\, e_{ae} \sin \frac{\pi}{6}$$

Hence,

$$e_f = 1.350\, e_{ae} \tag{23}$$

3.3 <u>Voltage Harmonics</u>[6]

The output voltage of a rectifier consists of a ripple, with a frequency three times the supply frequency, superposed on a steady d-c voltage. In present analysis it is assumed that the frequency of the ripple is same as the supply frequency. The harmonic content of an output wave may be determined by Fourier analysis. The harmonic content of an output wave from is illustrated by Fig. 11. The output voltage of a p-anode rectifier may be expressed by

$$e(\theta) = A_o + \sum_{1}^{m} (A_m \cos mp\theta + B_m \sin mp\theta) \tag{24}$$

where A_o is average value of output voltage as given by expression 23. A_m and B_m, the amplitudes of the harmonic components of the output wave, are given by the Fourier relations

$$A_n = \frac{p}{\pi} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} e(\theta) \cos n\theta \cdot d\theta \tag{25}$$

$$B_n = \frac{p}{\pi} \int_{-\frac{\pi}{p}}^{+\frac{\pi}{p}} e(\theta) \sin n\theta \cdot d\theta \tag{26}$$

where $n = mp$, with m an integer, is the order of the harmonic and $e(\theta) = e_{ae} \sqrt{2} \cos\theta$.

The evaluation of A_n and B_n gives

$$A_n = \pm \frac{2\, e_f}{n^2 - 1} \tag{27}$$

$$B_n = 0 \tag{28}$$

Taking third harmonic into consideration expression (24) reduces to

$$e(\theta) = A_o + 0.25 \quad e_f \quad \cos 3\theta \tag{29}$$

Substituting for A_o,

$$e(\theta) = 1.35\, e_{ae} + 0.25\, (1.35\, e_{ae}) \cos 3\theta$$

$$= 1.35\, e_{ae} + 0.3375\, e_{ae} \cos 3\theta$$

Since $\theta = \omega t$

$$e(\theta) = 1.35\, e_{ae} + 0.3375\, e_{ae} \cos 3\omega t \tag{30}$$

The output of the bridge rectifier, considering third harmonic, is

$$e_f = 1.35\, e_{ae} + 0.3375\, e_{ae} \cos 3\omega t \tag{31}$$

IV

SIMULATION OF MACHINE EQUATIONS

4.1 Digital Analog Program[7]

Pactolus might be described as a block-oriented interpretive language with on-line control and input-output capabilities. It was developed using Fortran II-D for the IBM 1620 with 10K memory, Card Read-Punch, 1311 Disk, and the 1627 Plotter. Patchboard wiring is accomplished via the typewriter in a simple format and also via punched cards.

The program incorporates all the standard analog computer elements like summing amplifiers, inverters, integrators, multipliers, relays, plus many special purpose analog circuits. The program is presently limited to maximum 75 elements. No more than 25 integrators can be used.

The second-order Runge-Kutta integration scheme used in Pactolus, provides fairly accurate method for solving simultaneous differential equations of the synchronous machine. Arithmetic is done single precision and floating point mode. Since the digital computer is a serial device, the program is incapable of handling an algebraic loop.

4.2 A.C. Exciter

The a.c. exciter may be represented by a simple transfer function which includes the predominant time constant of the exciter field. It therefore ignores all self and mutual inductances involving the armature and reflects only the open circuit time constant. The terminal voltage of the exciter in the steady state is related to the field voltage by the constant gain k_v.[8]

The phase A voltage of the a.c. exciter can be related to its field voltage as

$$e_{ae} = \frac{k_v}{1+\tau p} e_{fe} \tag{33}$$

Eq. (33) can be written as

$$\tau \, p \, e_{ae} + e_{ae} = k_v \cdot e_e$$

$$p \, e_{ae} = \frac{k_v}{\tau} \cdot e_{fe} - \frac{1}{\tau} e_{ae} \tag{34}$$

4.3 Rectifier

The output of the full-wave rectifier can be represented by Eq. (31). The third harmonic cosine function is generated by cosine block of the Pactolus subroutine.

$$e_f = 1.35 \, e_{ae} + 0.3375 \, e_{ae} \cos 3\omega t \tag{35}$$

4.4 Synchronous Generator

The formulation of the machine equation for analog representation can be done by considering the equivalent circuit as shown in Figs. 5 and 6 of Section 2.7.

Treating $p\psi_d$ as an applied voltage, the direct axis equations are,

(a) $$p\psi_d = l_a \, p \, i_d + L_{md} \, p \, (i_d + i_{kd} + i_f) \tag{36}$$

$$pi_d = \frac{1}{L_d} p\psi_d - \frac{L_{md}}{L_d} pi_{kd} - \frac{L_{md}}{L_d} p \, i_f \tag{37}$$

where $L_d = L_{md} + l_a$.

Similarly,

(b) $$e_{kd} = r_{kd}\, i_{kd} + l_{kd}\, p\, i_{kd} + L_{md}\, p\,(i_d + i_f + i_{kd})$$
$$e_{kd} = 0 \qquad (38)$$

Hence

$$p\, i_{kd} = -\frac{r_{kd}}{L_{kd}}\, i_{kd} - \frac{L_{md}}{L_{kd}}\, p\, i_d - \frac{L_{md}}{L_{kd}}\, p\, i_f \qquad (39)$$

where

$$L_{kd} = L_{md} + l_{kd}$$

(c) $$e_f = r_f\, i_f + l_f\, p\, i_f - r_{kd}\, i_{kd} - l_{kd}\, p\, i_{kd} \qquad (40)$$

hence

$$p\, i_f = \frac{1}{l_f}\, e_f - \frac{r_f}{l_f}\, i_f + \frac{r_{kd}}{l_f}\, i_{kd} + \frac{l_{kd}}{l_f}\, p\, i_{kd} \qquad (41)$$

Similarly treating $p\psi_q$ as an applied voltage the quadrature axis equations are,

(d) $$p\psi_q = l_a p\, i_q + L_{mq}\, p\,(i_q + i_{kq}) \qquad (42)$$

hence

$$p\, i_q = \frac{1}{L_q}\, p\psi_q - \frac{L_{mq}}{L_q}\, p\, i_{kq} \qquad (43)$$

where $L_q = L_{mq} + l_a$.

(e) $$e_{kq} = (r_{kq} + l_{kq}\, p)\, i_{kq} + L_{mq}\, p\,(i_q + i_{kq})$$
$$e_{kq} = 0$$

hence

$$p\, i_{kq} = -\frac{r_{kq}}{L_q}\, i_{kq} - \frac{L_{mq}}{L_q}\, p\, i_q \qquad (44)$$

Equations (37), (39), (41), (43), and (44) need manipulation to avoid the algebraic loop which is inacceptable for Pactolus representation.

Eliminating pi_d from Eq. (39), pi_{kd} from Eq. (41) and pi_q from Eq. (44), following equations are obtained

$$p\, i_{kd} = -\, k_1\, i_{kd} + k_2\, p\, i_f - k_3\, p\, \psi_d \tag{45}$$

$$p\, i_f = m_1\, e_f - m_2\, i_f + m_3\, i_{kd} - m_4\, p\, \psi_d \tag{46}$$

and

$$p\, i_{kq} = -\, g_1\, i_{kq} - g_2\, p\, \psi_q \tag{47}$$

where

$$k_1 = \frac{r_{kd}/L_{kd}}{\left(1 - \frac{L_{md}^2}{L_d \cdot L_{kd}}\right)}$$

$$k_2 = \frac{\frac{L_{md}^2}{L_d \cdot L_{kd}} - \frac{L_{md}}{L_{kd}}}{\left(1 - \frac{L_{md}^2}{L_d \cdot L_{kd}}\right)}$$

$$k_3 = \frac{L_{md}/L_{kd} \cdot L_d}{\left(1 - \frac{L_{md}^2}{L_d \cdot L_{kd}}\right)}$$

$$m_1 = \frac{1/l_f}{\left(1 - \frac{l_{kd}}{l_f} \cdot k_2\right)}$$

$$m_2 = \frac{r_f/l_f}{\left(1 - \frac{l_{kd}}{l_f} \cdot k_2\right)}$$

$$m_3 = \frac{\left(\frac{r_{kd}}{l_f} - \frac{l_{kd}}{l_f} \cdot k_1\right)}{\left(1 - \frac{l_{kd}}{l_f} \cdot k_2\right)}$$

$$m_4 = \frac{\frac{l_{kd}}{l_f} \cdot k_3}{\left(1 - \frac{l_{kd}}{l_f} \cdot k_2\right)}$$

$$g_1 = \frac{r_{kq}/L_q}{\left(1 - \frac{L_{mq}^2}{L_q^2}\right)}$$

$$g_2 = \frac{\frac{L_{mq}}{L_q^2}}{\left(1 - \frac{L_{mq}^2}{L_q^2}\right)}$$

Integrating Eqs. (37), (43), (45), (46), (47) we obtain the set of equations ready for simulation.

$$i_{kd} = -k_1 \int_0^t i_{kd} \cdot dt + k_2 \cdot i_f - k_3 \psi_d \tag{48}$$

$$i_f = \int_0^t (m_1 \cdot e_f - m_2 \cdot i_f + m_3 \cdot i_{kd})dt - m_4 \psi_d \tag{49}$$

$$i_{kq} = -g_1 \int_0^t i_{kq} \cdot dt - g_2 \psi_q \tag{50}$$

$$i_d = \frac{1}{L_d} \psi_d - \frac{L_{md}}{L_d} i_f - \frac{L_{md}}{L_d} i_{kd} \tag{51}$$

$$i_q = \frac{1}{L_q} \psi_q - \frac{L_{mq}}{L_q} i_{kq} \tag{52}$$

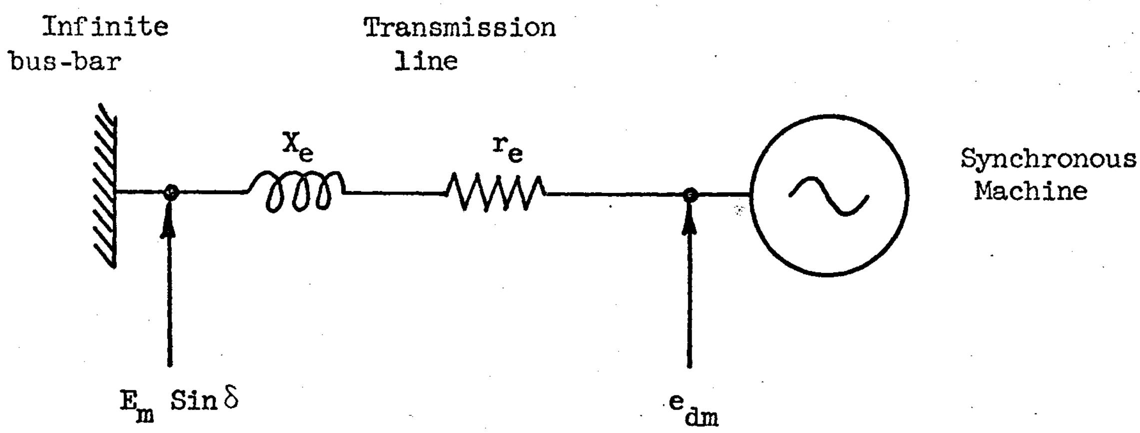


Fig:12 Representation of transmission line and infinite bus-bar.

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4.5 Infinite Bus and Transmission Line

Transmission line or external reactance between machine terminals and the infinite bus-bar can be represented[9] by a resistance r_e and a reactance X_e as shown in Fig. 12. Eqs. (10), (11) are modified to

$$e_{dm} = E_m \cdot \sin\delta - X_e \cdot i_q - r_e \cdot i_d = p\psi_d + \omega_o \psi_q - \psi_q p\delta + r_a \cdot i_d \tag{53}$$

$$e_{qm} = E_m \cdot \cos\delta + X_e \cdot i_d - r_e \cdot i_q = \omega_o \psi_d + \psi_d\, p\delta + p\psi_q + r_a \cdot i_q \tag{54}$$

Eqs. (53) and (54) are modified for Pactolus representation to

$$p\psi_d = E_m \sin\delta - \omega_o \psi_q + \psi_q p\delta - (r_a + r_e) i_d - X_e \cdot i_q \tag{55}$$

$$p\psi_q = E_m \cos\delta + \omega_o \psi_d - \psi_d p\delta - (r_a + r_e) i_q + X_e i_d \tag{56}$$

The terminal voltage of the machine was recorded by simulating the following equations:

$$e_{dm} = E_m \sin\delta - X_e\, i_q - r_e \cdot i_d \tag{57}$$

$$e_{qm} = E_m \cos\delta + X_e\, i_d - r_e \cdot i_q \tag{58}$$

$$et = \sqrt{\frac{(e_{dm}^2 + e_{qm}^2)}{2}} \tag{59}$$

$$i_a = \sqrt{\frac{i_d^2 + i_q^2}{2}} \tag{60}$$

4.6 Torque Equation

From Section 2.8, Eq. (22) can be rearranged for simulation as follows

$$p^2\delta = \frac{\omega_o^2}{4H} (\psi_d i_q - \psi_q i_d) - \frac{\omega_o}{2H} f_t \tag{61}$$

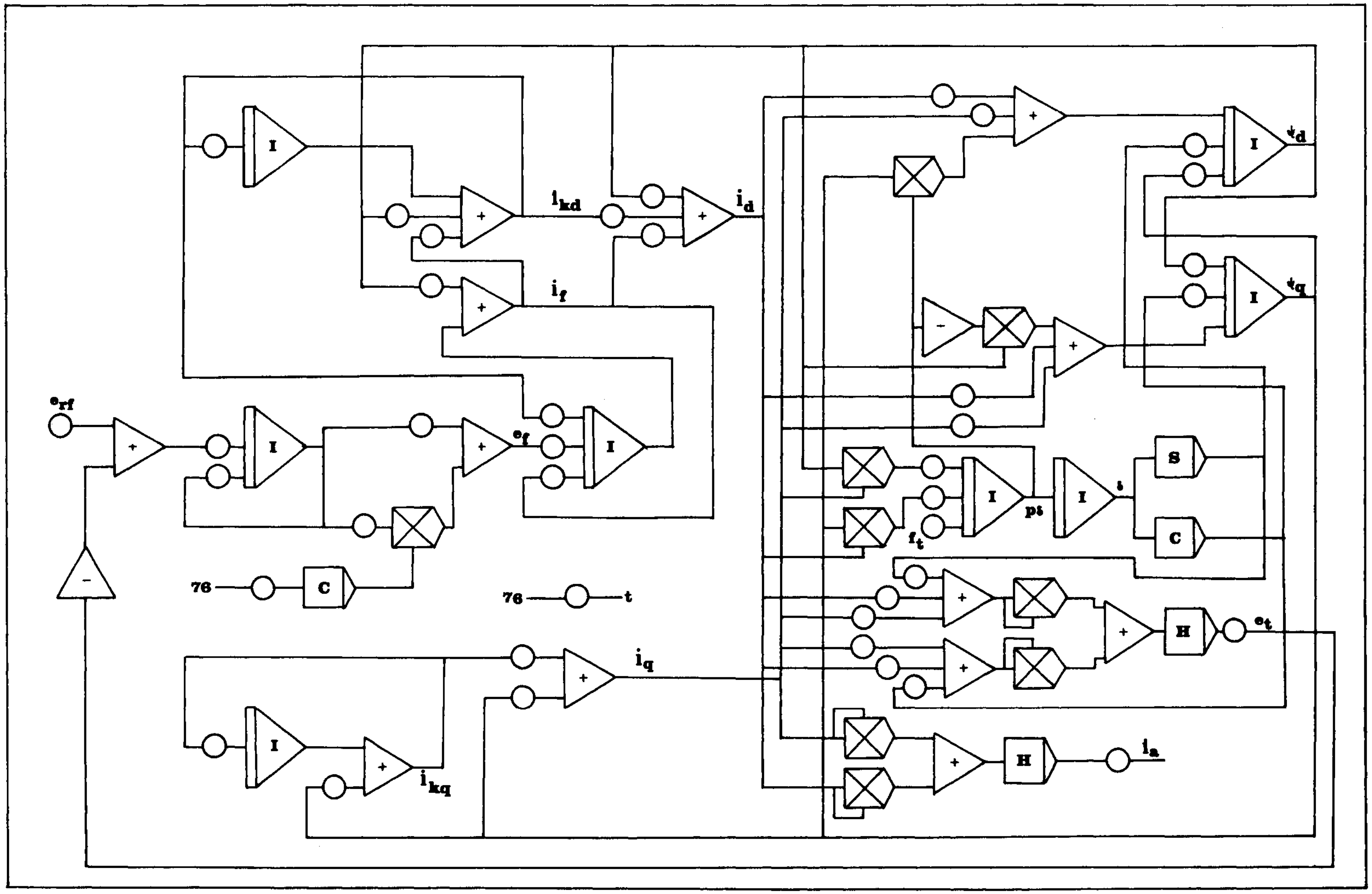


Fig: 13 PACTOLUS representation for the voltage regulation studies of a Brushless Synchronous Generator connected to an infinite bus-bar through a transmission line.

[Factors such as scales,sign etc. are omitted]

Legend of the Block Diagram

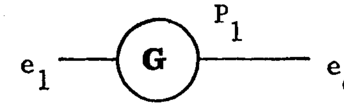
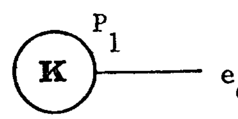
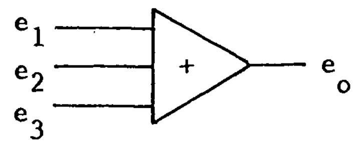
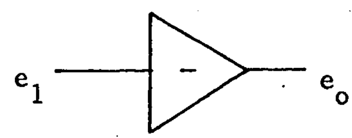
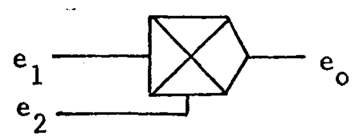
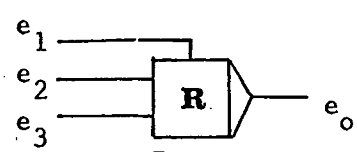
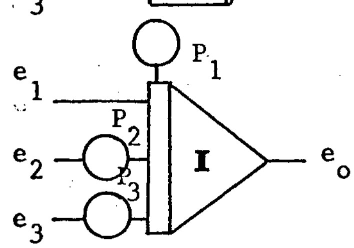
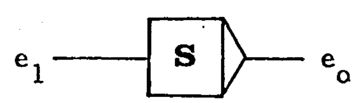
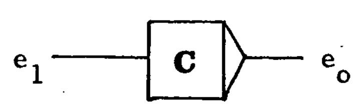
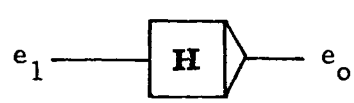
Name	Type	Symbol	Description
Gain	**G**		$e_o = P_1 \cdot e_1$
Constant	**K**		$e_o = P_1$
Summer	+		$e_o = \pm e_1 \pm e_2 \pm e_3$
Sign Inverter	–		$e_1 = -e_1$
Multiplier	**X**		$e_o = e_1 \cdot e_2$
Relay	**R**		$e_o = \begin{matrix} e_2 \\ e_3 \end{matrix}$ for $\begin{matrix} e_1 \geq 0 \\ e_1 < 0 \end{matrix}$
Integrator	**I**		$e_o = P_1 + \int (e_1 + e_2 P_2 + e_3 P_3 dt)$
Sine	**S**		$e_o = \sin(e_1)$ argument in radians
Cosine	**C**		$e_o = \cos(e_1)$ argument in radians
Half Power	**H**		$e_o = \sqrt{e_1}$ square root
Time base		**76**	

Fig. 14

4.7 Feedback Loop

In the study of closed loop system, the terminal voltage is dropped down by a potential transformer and rectified to get voltage of small magnitude. All effects due to potential transformer and rectifier unit are neglected and only simple transformation is assumed. The reference voltage e_{rf} is compared with the feedback signal, and the difference in the form of an error is fed to the a.c. exciter field. The exciter input voltage e_{ae} is related as

$$e_{ae} = e_{rf} \pm e_{er}$$

4.8 Solution by Digital-Analog Simulator Program

Fig. 13 shows the block diagram for the simultaneous solutions of Eqs. (34), (35), (48), (49), (50), (51), (52), (55), (56), (57), (58),(61), (59), (60) on IBM 1620 digital computer. All factors such as scales, sign, parameters, etc., are omitted for simplicity of the diagram. The studies performed and the results are mentioned in the next chapter.

The machine parameters are given in Appendix I[9]. No experimental verification is done which makes this thesis a purely theoretical one.

V

DISCUSSION OF THE RESULTS

5.1 Operating Procedure

The simulation configuration is the specification of the interconnection of the computing blocks, where each block is one of the standard set of 'Pactolus' elements. Fig. 13 shows the complete simulation diagram for solution of a set of simultaneous differential equations, as stated in Section 4.8. The integration interval of 0.001 sec. was found to give enough accuracy and hence it was maintained throughout the course of different studies. A relay was introduced at 0.4 sec., to create the necessary condition (Fig. 14). In the following sections various studies performed on the system will be discussed.

5.2 Step Change Test

In this section voltage response of the synchronous generator connected to an infinite bus-bar through a transmission line, to step change in the reference setting is examined. The step demand is satisfied by quick response in terminal voltage e_t, in less than 1.5 sec. The drop in load current i_a, and load angle δ is obvious. The field current also rises in order to meet the requirement of the higher voltage level. Since the generator is connected to a constant voltage source the rise will always be less than unity. Good steady state agreements between stator voltage, current and rotor angle show that the method used is satisfactory. It is shown in Fig. 15,16.

Response Curve of Terminal Voltage and Load Current for a Step Change

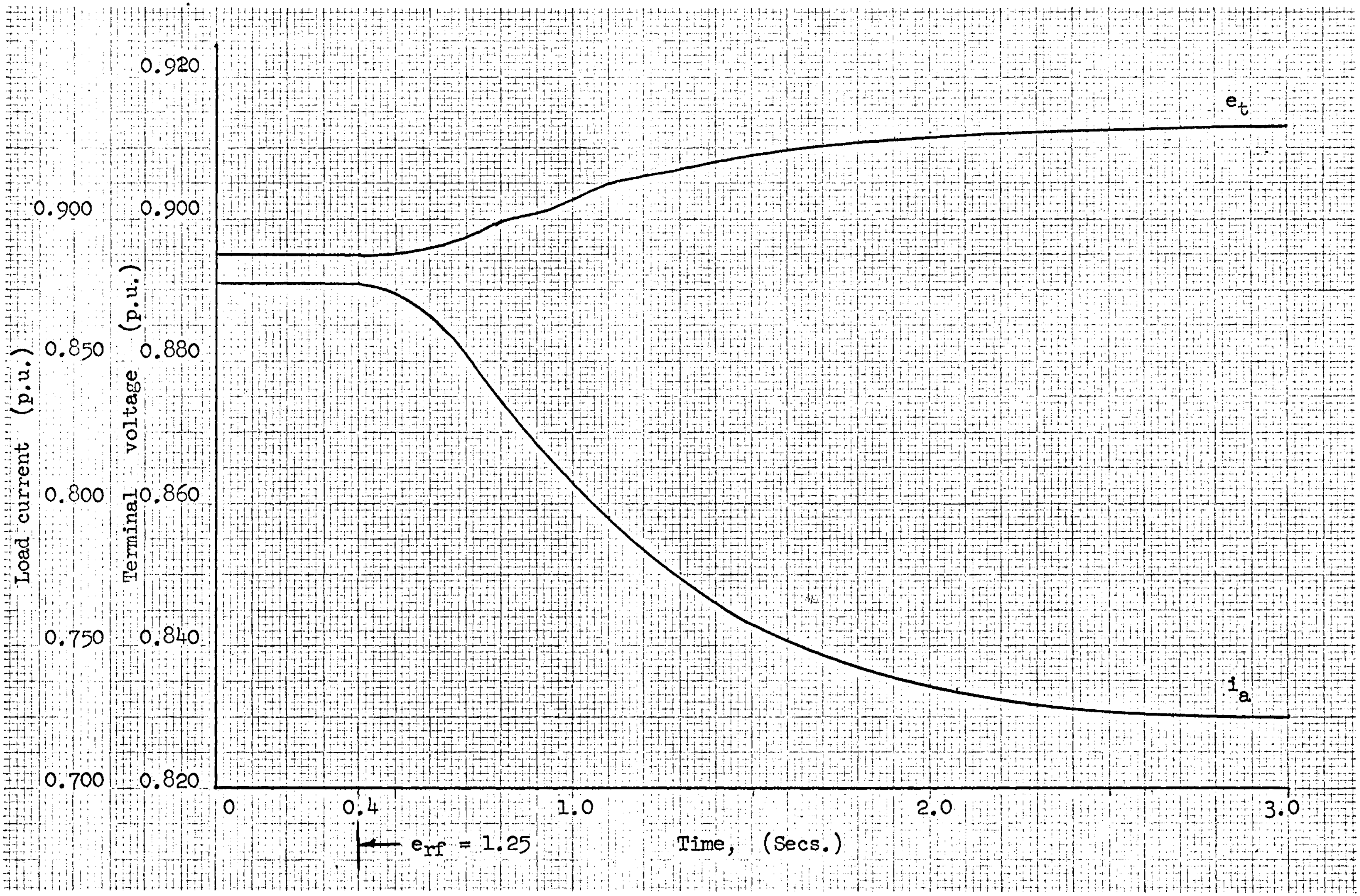


Fig. 15

Response Curve of Field Current and Load Angle for a Step Change

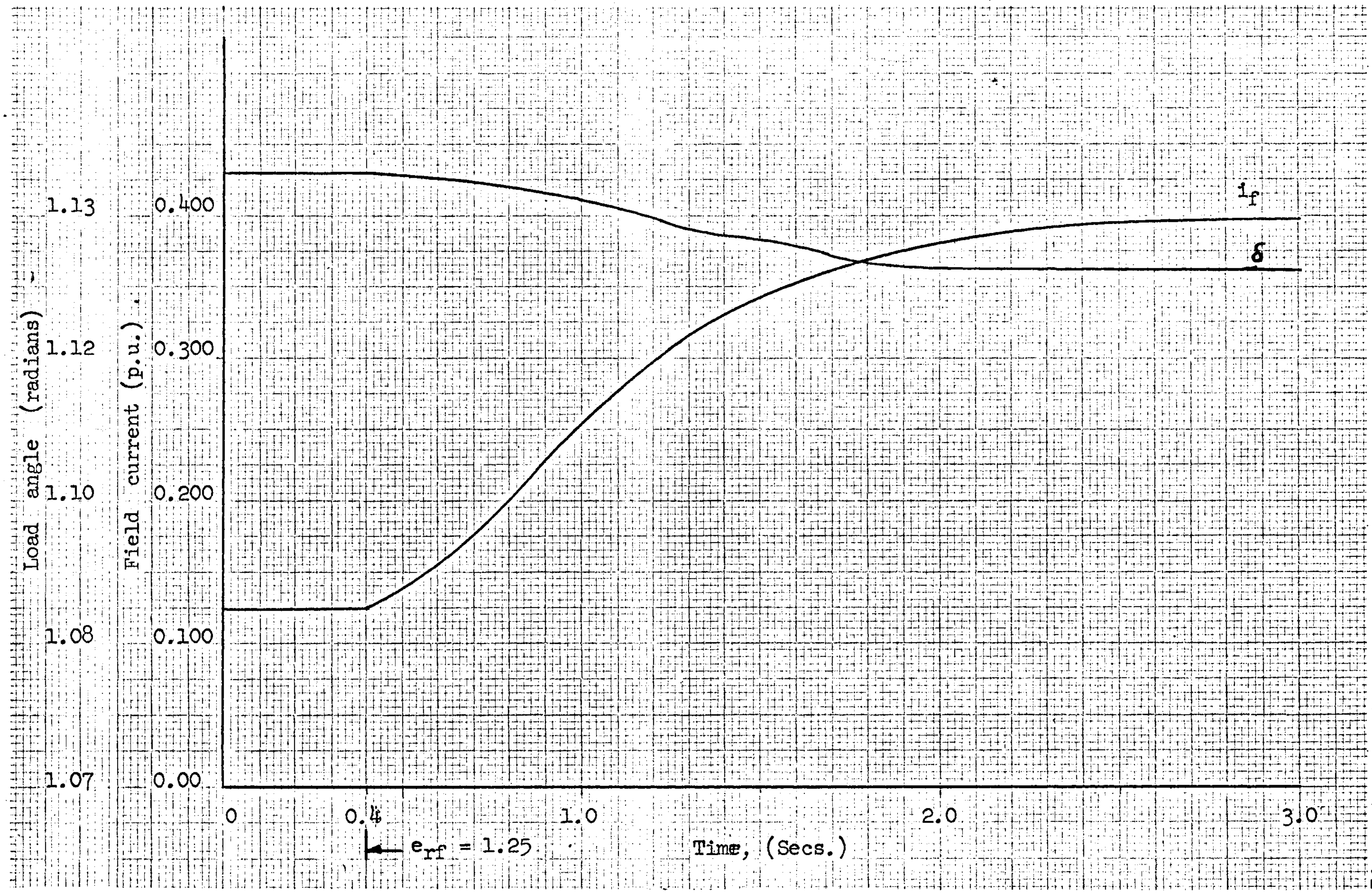


Fig. 16

5.3 Load Rejection and Acceptance Test

In complex power system network the generator is subjected to various types of loading conditions. The extreme cases that generator has to face would be sudden rejection of load to zero. The generator in the present study is connected to a infinite bus, through a transmission line reactance. The load rejection condition is initiated by reducing turbine torque f_t to zero. A momentary drop in terminal voltage adjusted itself by voltage regulator action to its original value in less than a second. Other quantities such as line current and load angle dropped down as expected. (Fig. 17,18)

In the next case, generator running in steady state condition was subjected to sudden increase in load by making $f_t = 2.00$ p.u.. A drop of 0.125% was observed in terminal voltage which is supposed to be a good regulation characteristics. The load angle and current increased gradually stabilizing the system in less than 2 seconds. (Fig. 19,20)

5.4 Gain Increasement

The increase in exciter gain increases the output voltage of the synchronous generator. In the first case (Fig.21,22) the gain is increased by 25% of the original value and an approximate increase of 0.25% of the original value in terminal voltage was observed. The corresponding increase in field current is found. The load angle δ reduces because of the increase in both the excitation voltage and terminal voltage of the machine. Load current decreases to compensate for the increase in the terminal voltage at constant power output.

Response Curve of Terminal Voltage and Load Current for Load Rejection Test

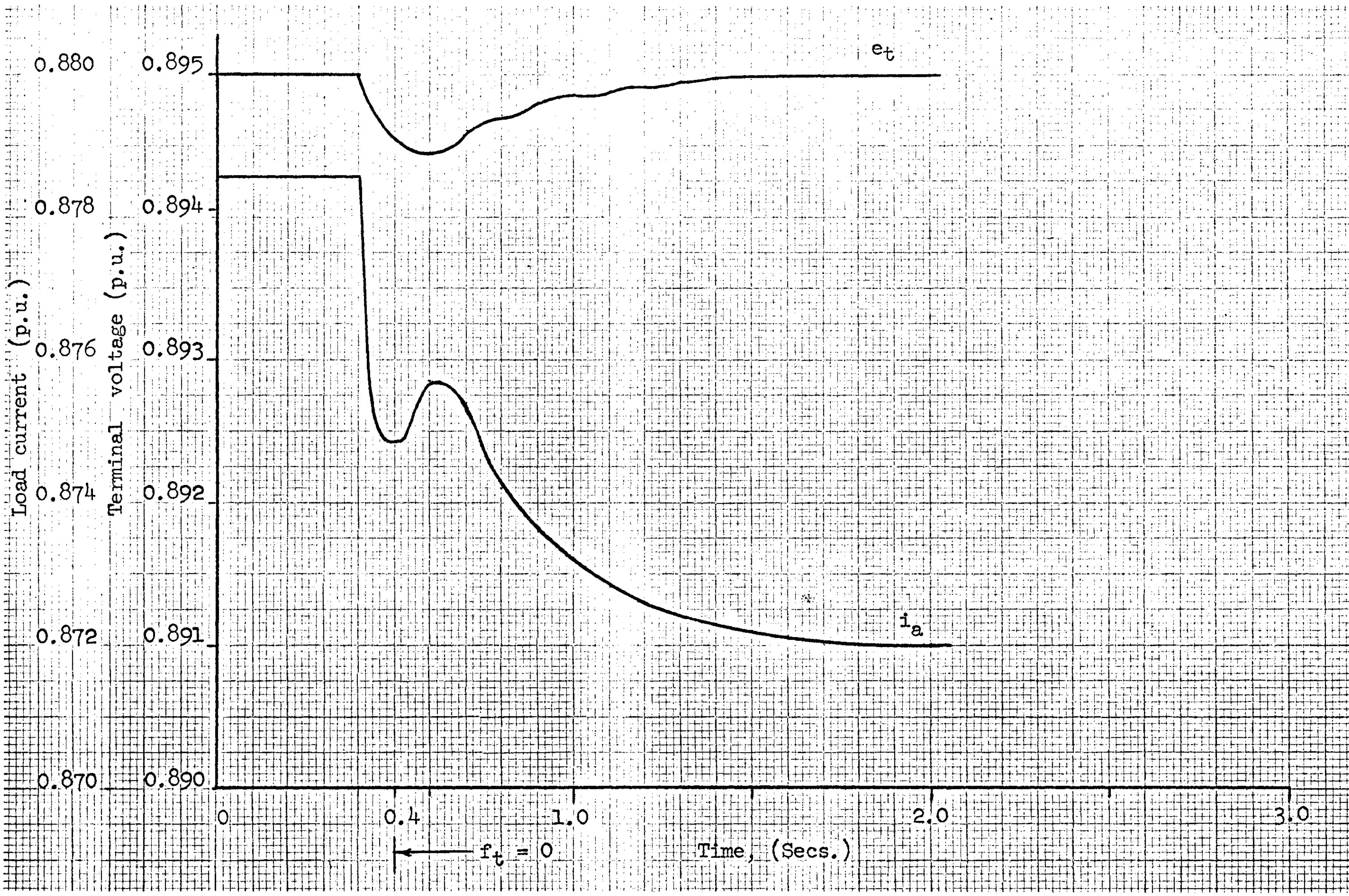


Fig. 17

Response Curve of Field Current and Load Angle for Load Rejection Test

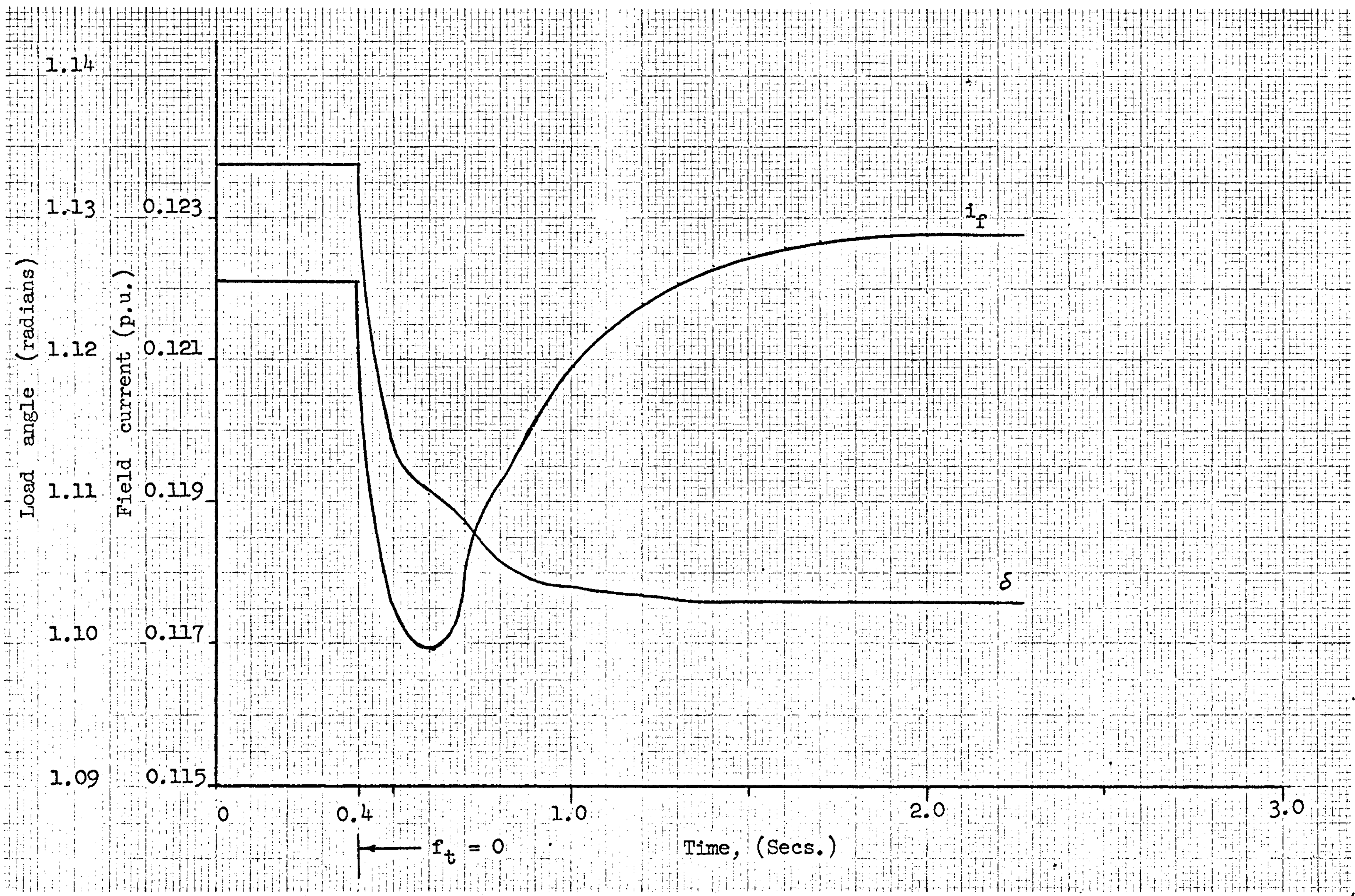


Fig. 18

Response Curve of a Terminal Voltage and Load Current for Load Acceptance Test

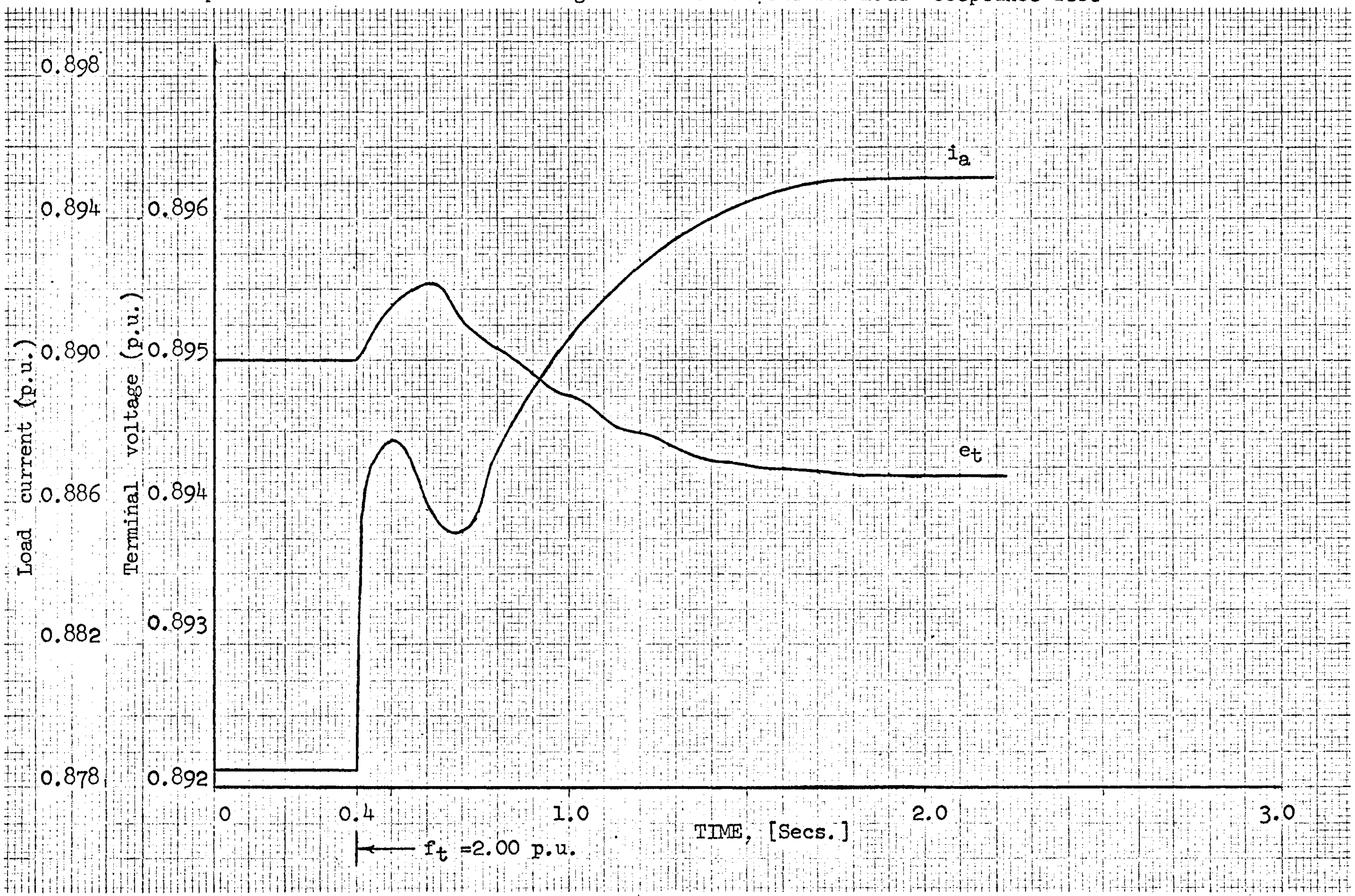


Fig. 19

Response Curve of a Field Current and Load Angle for Load Acceptance Test

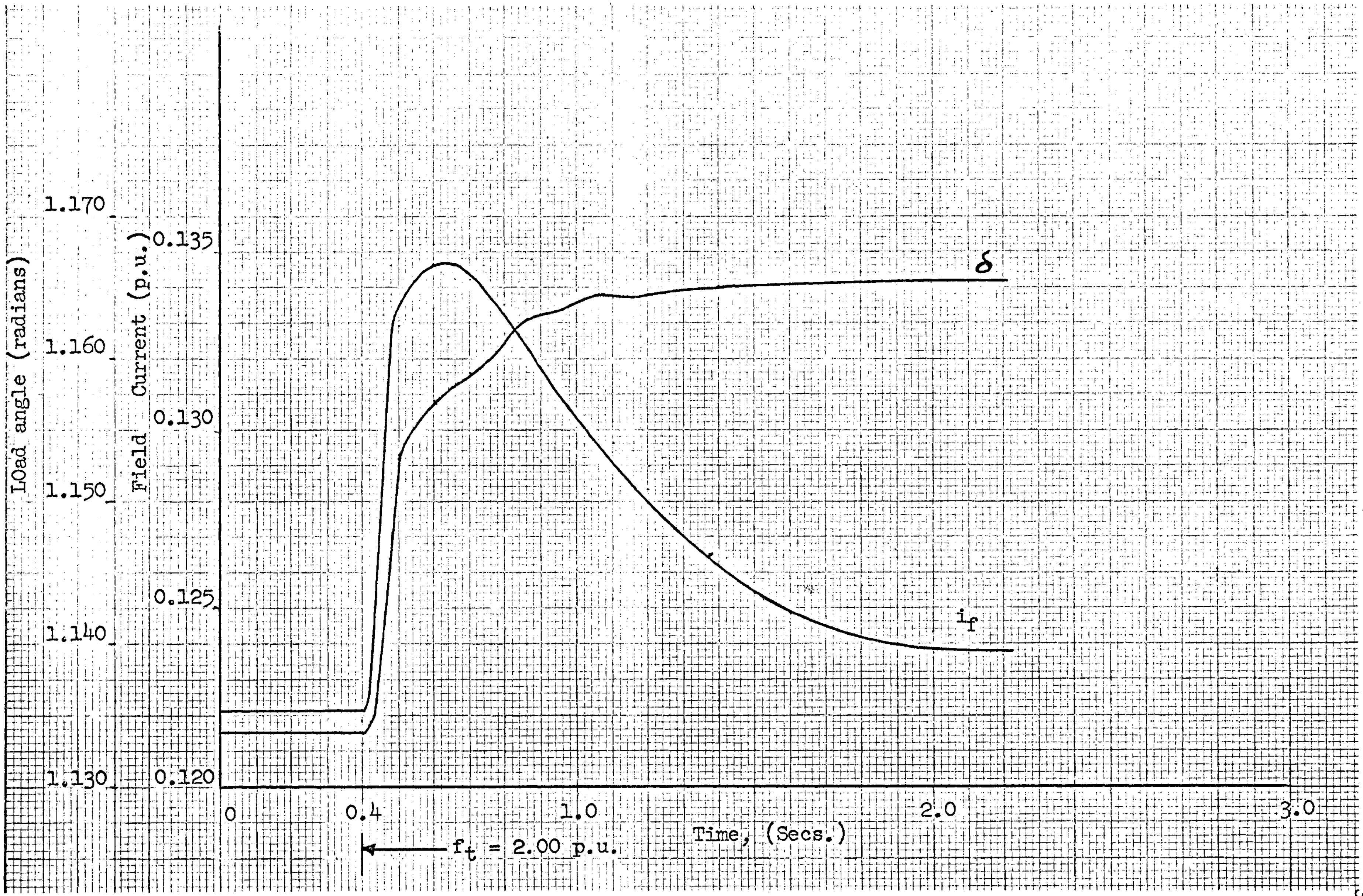


Fig. 20

Reponse Curve of a Terminal Voltage and Load Current for 25% increasement in gain k_v

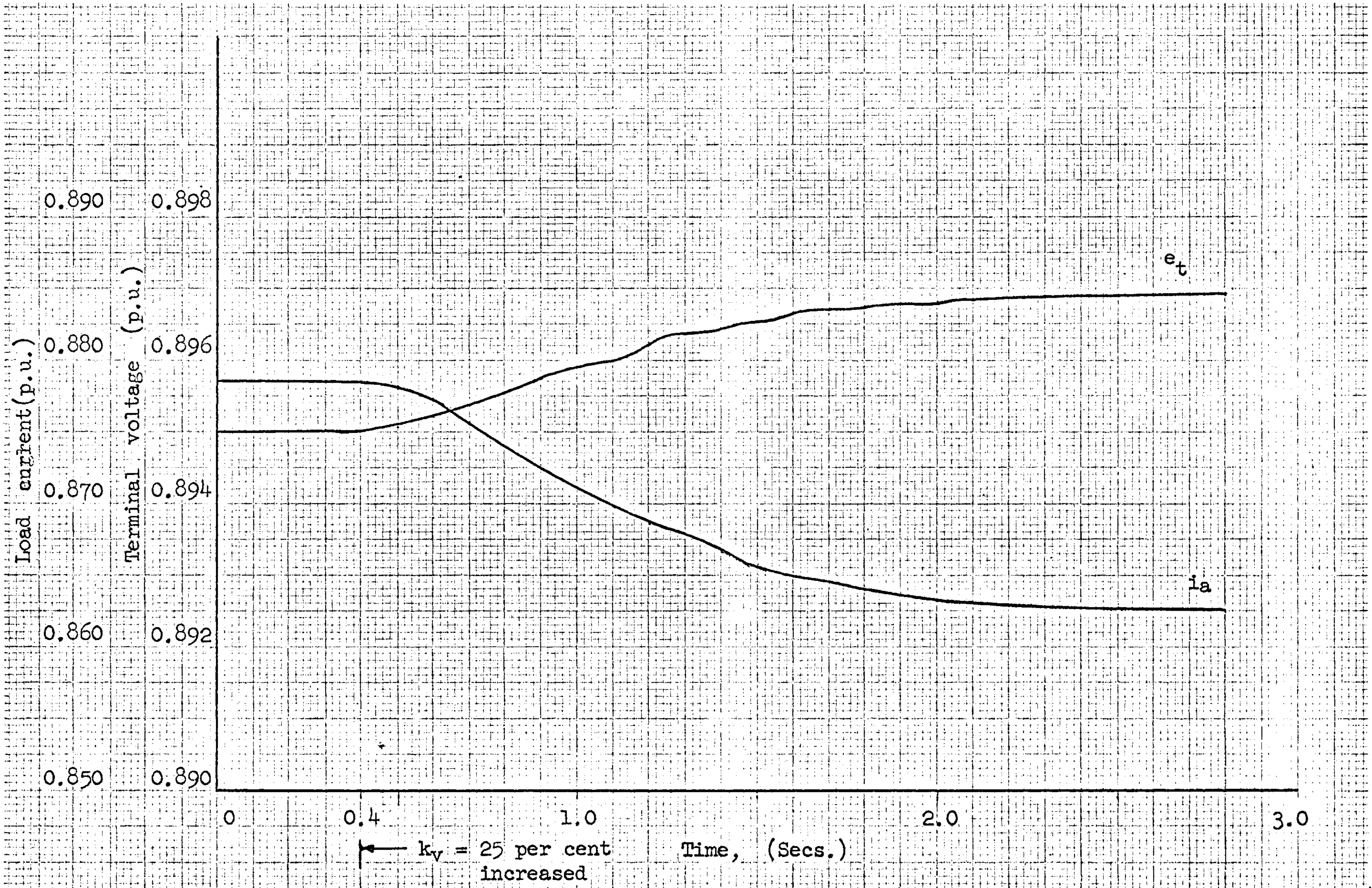


Fig. 21

Response Curve of a Field Current and Load Angle for 25% Increasement in gain k_v

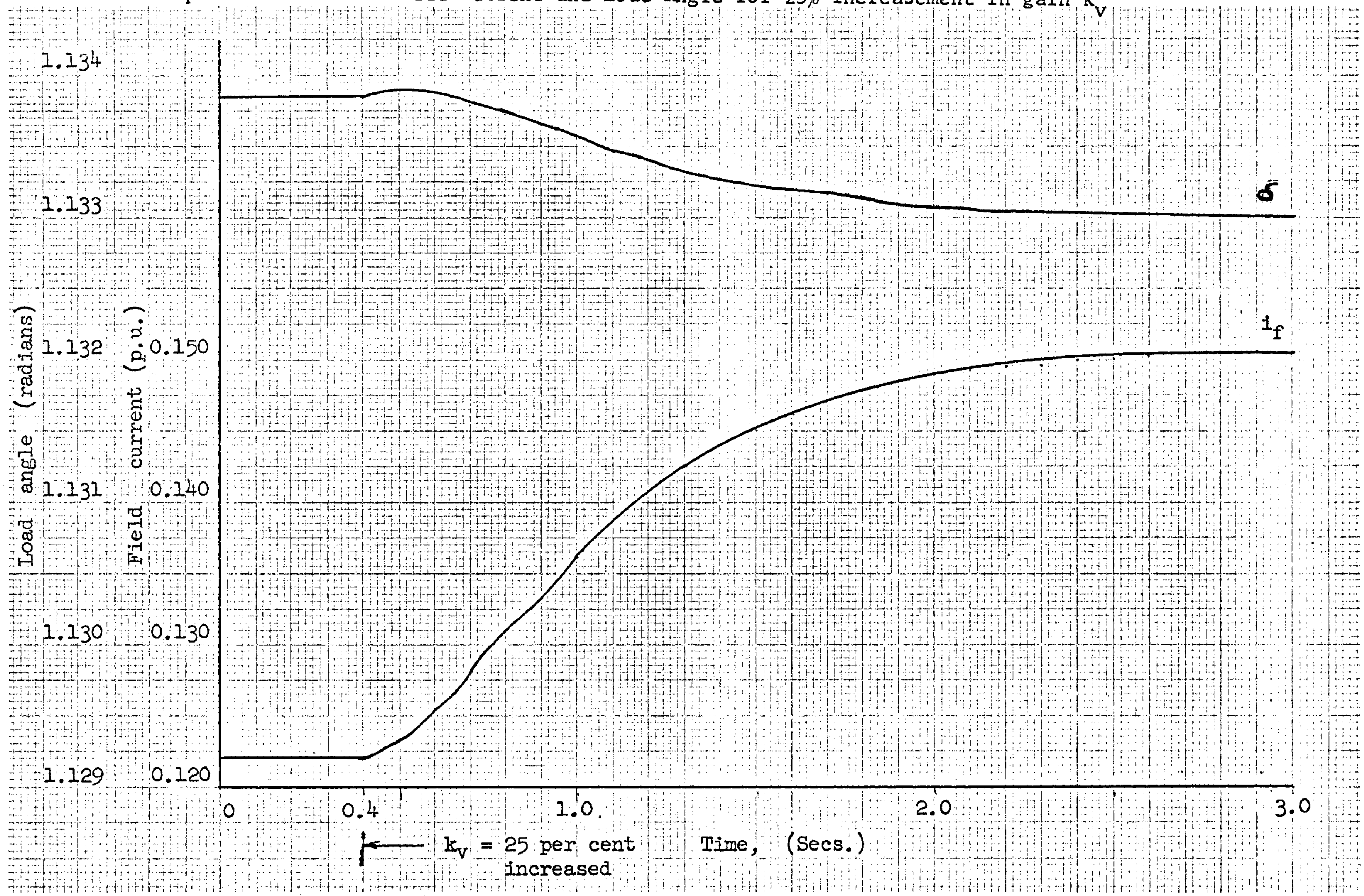


Fig. 22

In second case (Fig.23,24) the gain of the exciter is increased by 50% of its original value. It is very interesting to note that field current i_f increases to 41% of its original value, while in first case this is 23%. Though the system is nonlinear, the response appears to be a linear one. Other quantities vary exactly like in case 1.

The demand of higher operating voltage may thus be satisfied in fairly short period of time.

5.5 Neglecting the Third Harmonic

The third harmonic component being injected into the average value of the rectifier output was removed to observe the possible discrepancy in the results. The third harmonic component being very small no appreciable change was observed in e_t, i_a, i_f and δ, hence no results are plotted.

5.6 Response to a Small Sinusoidal Signal

A small sinusoidal signal having frequency 2 c.p.s. and magnitude 10% that of terminal voltage was injected at the reference. All quantities except load angle were found to be varying sinusoidally in their average value which are usually steady in nature. However a very small oscillating change was observed in load angle magnitude. (Fig. 25,26)

Response Curve of Terminal Voltage and Load Current for 50% Increasement in gain k_v

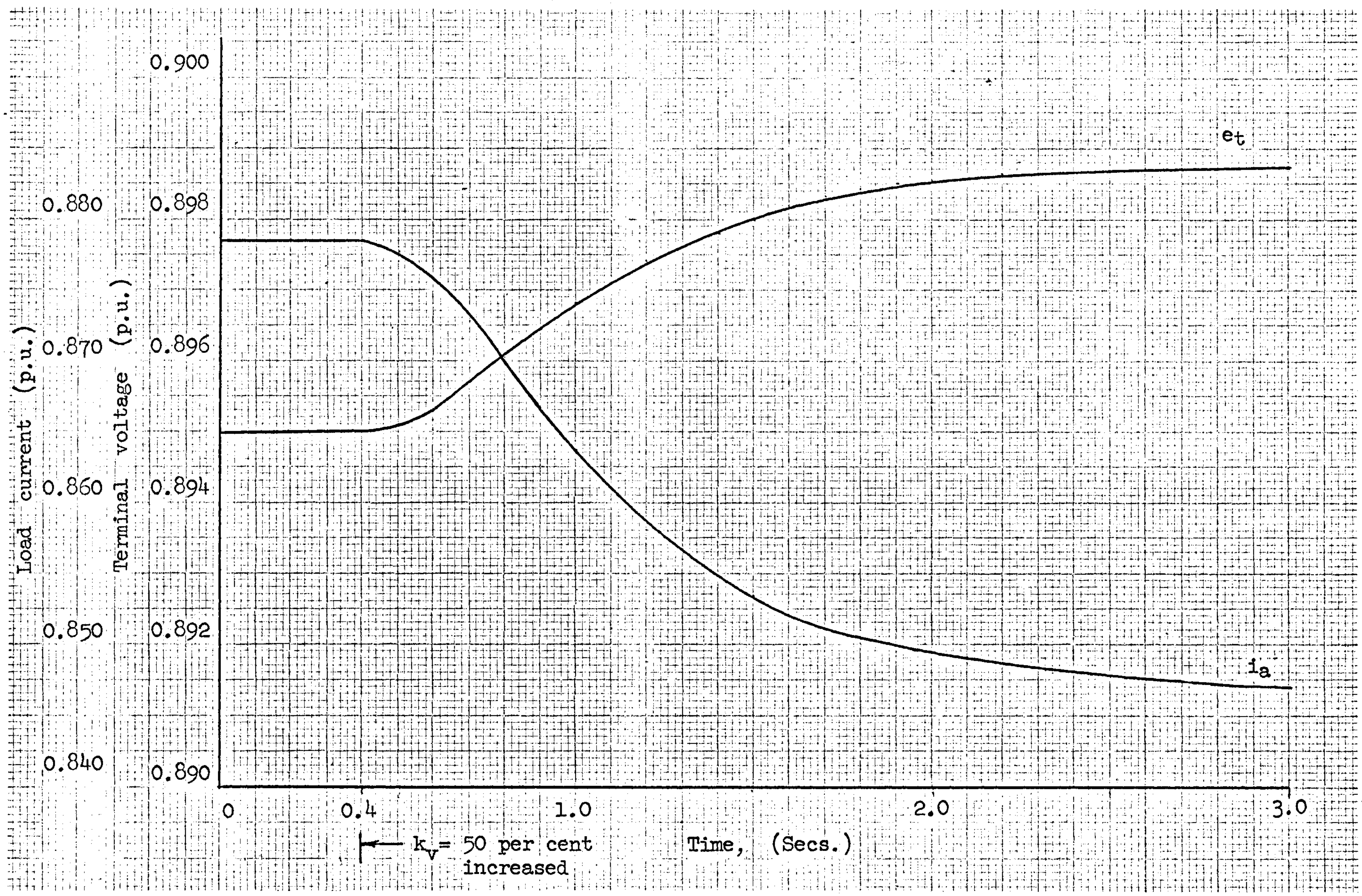


Fig. 23

Response Curve of Field Current and Load Angle for 50% Increasement in gain k_v

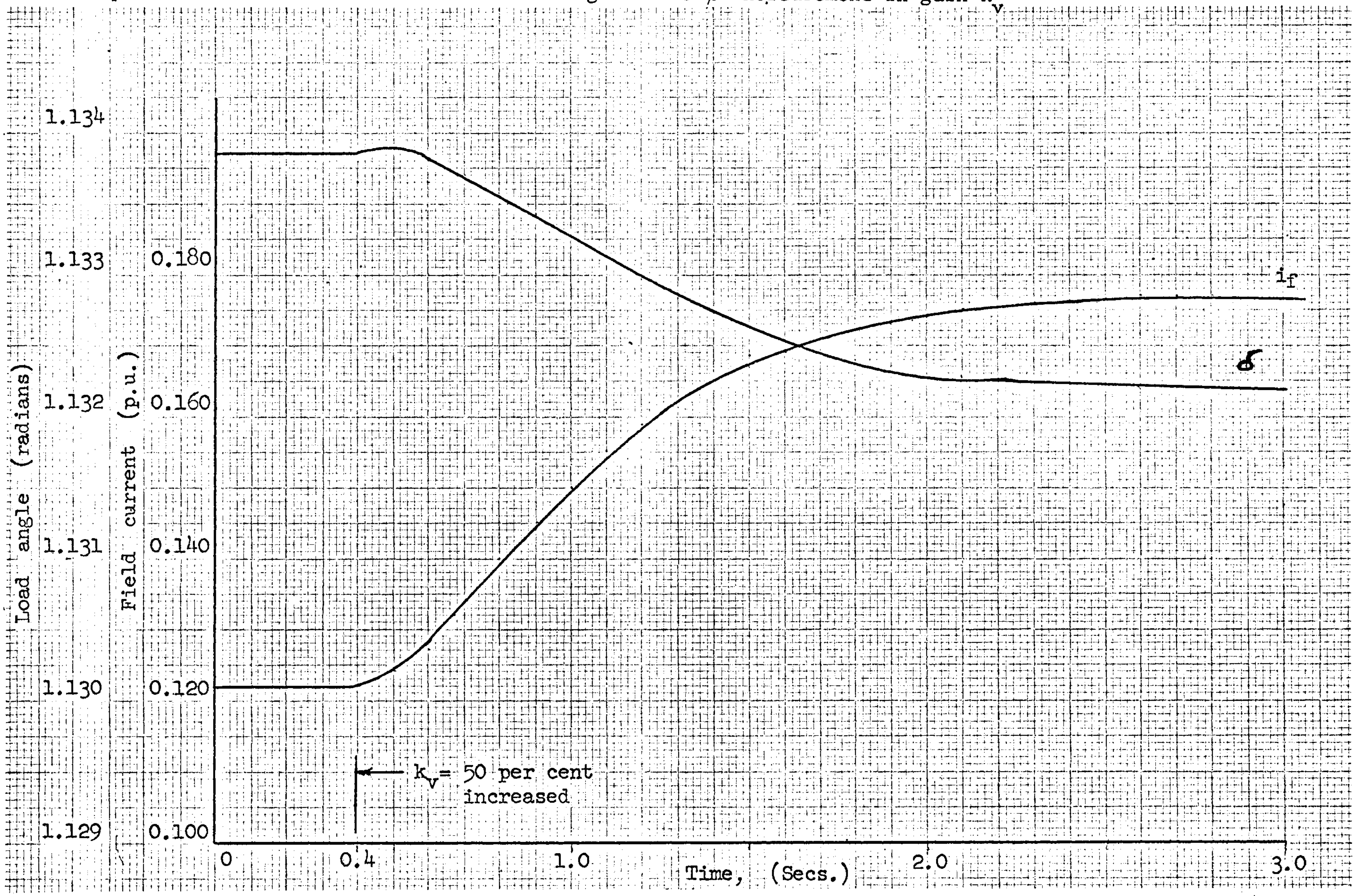


Fig. 24

Response Curve of Terminal Voltage and Load Current for a Small Sinusoidal Signal at Reference

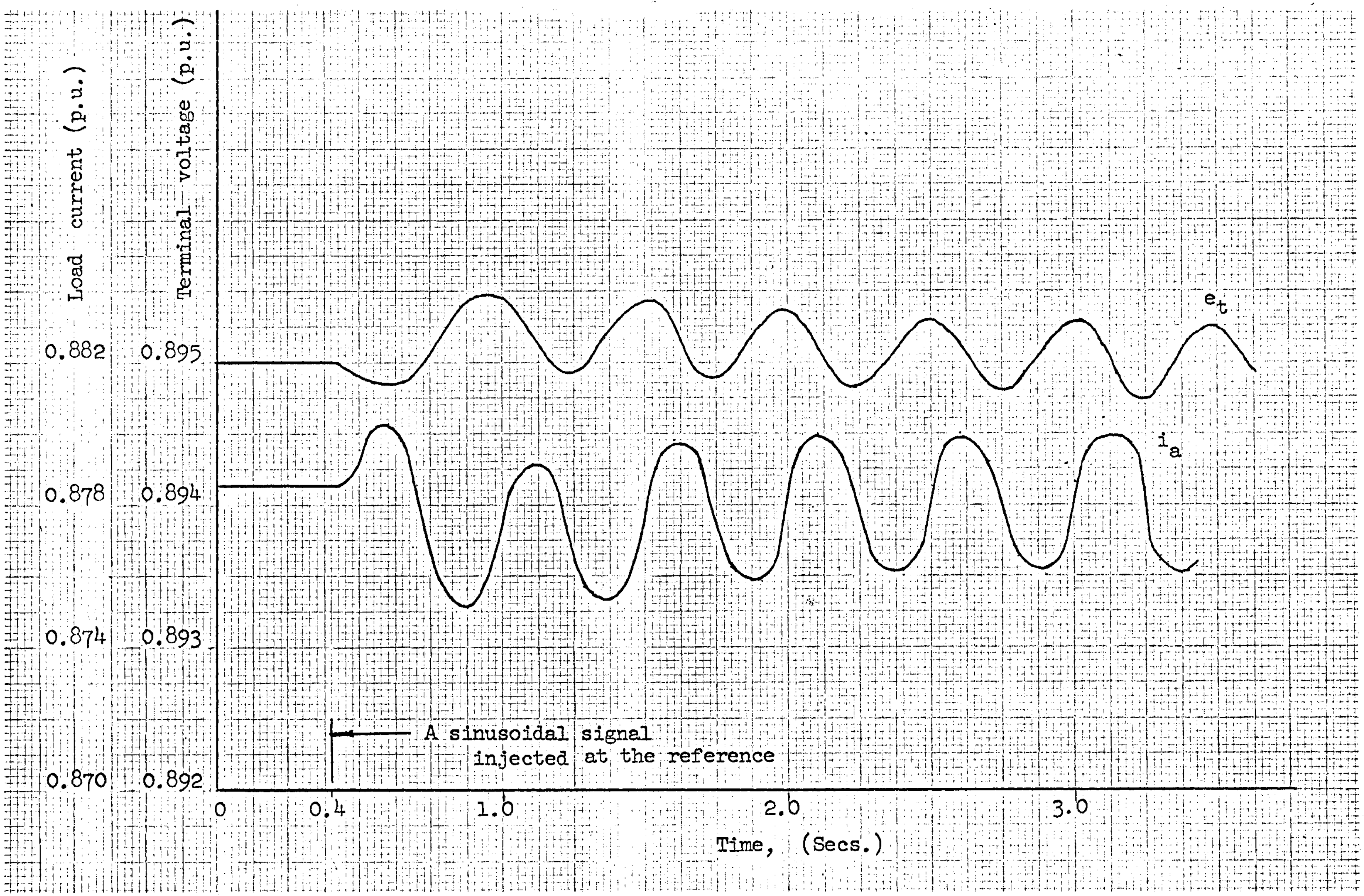


Fig. 25

Response Curve of Field Current and Load Angle for a Small Sinusoidal Signal at Reference

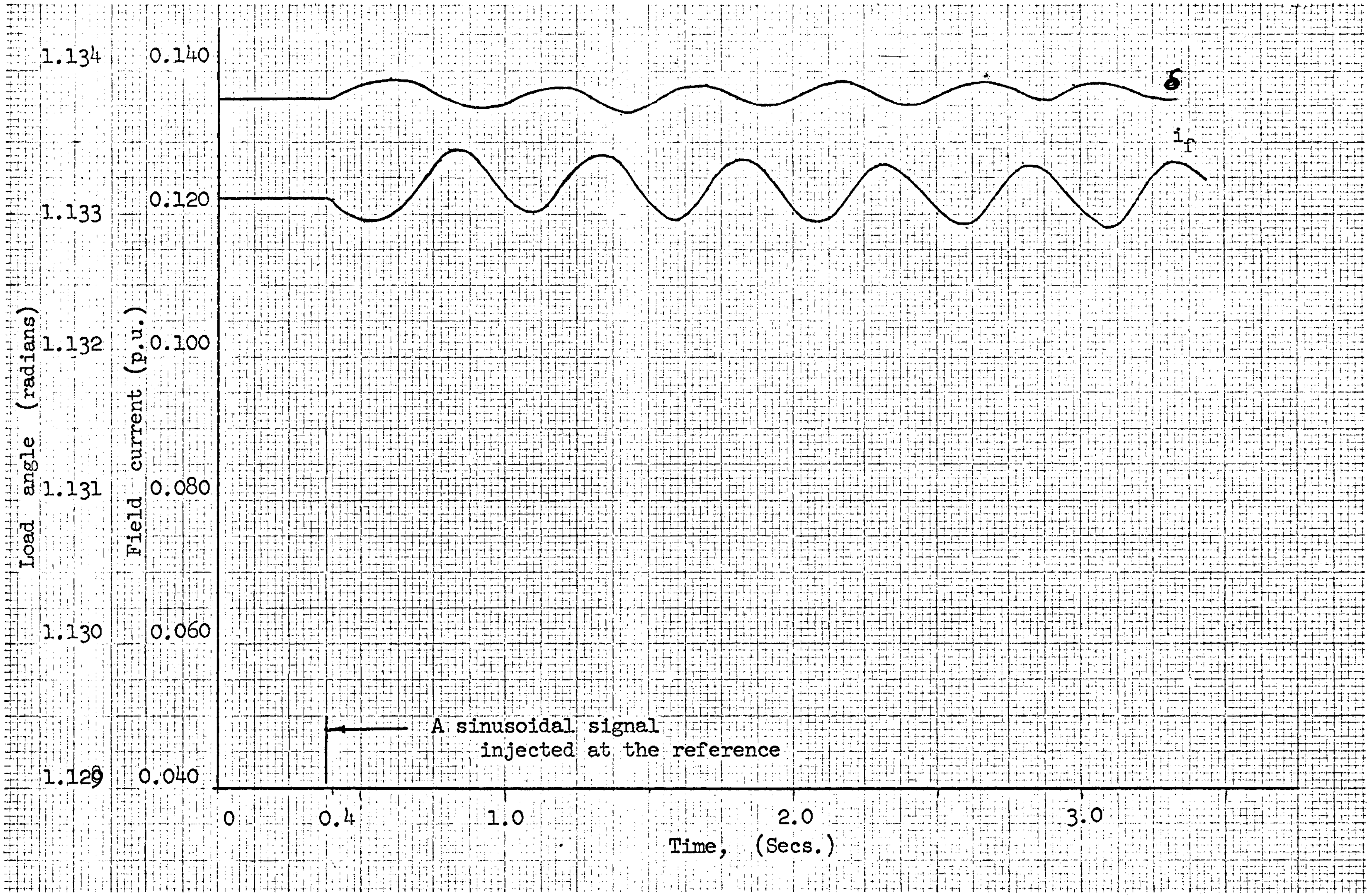


Fig. 26

VI

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The block-diagram representation as given in Fig. 13, yields the necessary information to specify the generator connected to infinite bus through transmission line, from a regulation standpoint of view. Studies have been satisfactorily completed on electronic analog computer in the past but the use of digital-analog technique have also justified the results in the present work. A physical insight into the dynamics of the machine is given by such representation which preserves the identity of the physical variables and uses parameters which are available from test or design data. The important advantage in this formulation of the dynamics of the brushless synchronous generator, is that the block diagram of the machine can be combined easily with the block diagram representations of other system components.

6.2 Recommendations

There could be various ways to make the representation as accurate as possible. The effect of saturation being neglected can be included. Limited number of blocks (75) that can be used at a time, compelled that the effect of certain factors be neglected. The exciter, for example could have been represented by fully developing the machine equation instead of considering the simple transfer function. The rectifier on the other hand is considered simply a device which gives average value of the rectified vaoltage. It could have been more interesting to consider an exact representation of the rectifier, as a switching device. A difficulty was experienced to relate the field current of the main generator to the line current of the exciter looking through the rectifier.

The Pactolus written for IBM 1620 computer, which is inherently slower than other members of its family is being replaced by more faster package programs like Midas and many others. The same results are achieved by IBM 360 or IBM 7040 computers at much faster rate.

APPENDIX I

Machine Data

1) A.C. Exciter

$\tau = 0.5$ sec

$k_v = 0.00446$

2) Synchronous Machine
Laminated rotor micro-machine

stator No. 334819

rotor No. 334818

Base Quantities

voltampere	1525 VA
voltage (per phase)	127 volts
current (per phase)	4 amps
impedence	31.75 ohms
field current	0.519 amps
synchronous speed	314 rad./sec
supply frequency	50 cps

Machine Parameters

All quantities are in per-unit unless otherwise stated.

r_a	0.007
r_f	0.00446
l_f	0.000677
l_a	0.00031
l_{kd}	0.000122

l_{kq}	0.000158
L_{md}	0.00268
L_{mq}	0.0015
r_{kd}	0.01463
r_{kq}	0.0176

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